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Performance testing as a means of industrial normalization of CSP technologies

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Abstract

An introduction to performance test codes applicable to concentrating solar power (CSP) is provided. An example of performance testing of a photovoltaic (PV) plant is used to show the methodology, since CSP industrial testing standards are unavailable at this time. The example case provides a discussion of the measurement requirements to evaluate the solar field. Finally, a brief introduction to uncertainty analysis is provided. The use and development of standard testing practices will eventually reduce testing uncertainty and provide a means for CSP and other renewable energy sources to be compared on an equal footing to traditional power industry technologies.

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1. Introduction

The demand for clean energy from renewable resources has grown increasingly strong in the last thirty years. Currently initiatives are underway to offset fossil fuel generation with clean energy alternatives. Traditional energy producers have relied on industrial standardized testing methods to evaluate the performance of their facilities not only for initial contractual acceptance but for long term degradation and maintenance evaluation. These performance tests can be accomplished by utility based testing services or in many cases by an outside testing agency. In either case, performance testing has long been a fundamental means of proving out a technology.

While the conversion of solar energy to electrical power is very different for CSP and PV, both technologies have similar industrial hurdles to overcome to obtain acceptance. Solar power plants in many respects are no different from traditional power facilities that convert useable fuel energy to electricity. The difference comes in the availability to produce power and a way for the power industry to quantify and qualify the performance of the

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technologies. Solar power facilities must be able to compete with traditional forms of power production in order to be considered a viable renewable alternative on a large scale. An accurate, standardized, and repeatable means of determining performance, similar to that for traditional forms of power generation, will enable this to be done. The American Society of Mechanical Engineers (ASME) has provided the power industry with a series of Performance Test Codes (PTC) to determine the performance of a power plant andits specific power plant components by taking a standardized approach. Currently, there are some test codes and guidelines appropriate to CSP either available or under development and will be discussed in more detail in Section 2.

In a recent article, Marion Hart posed the question, "How do you know a technology has truly arrived?" [1] The answer, from a technical point of view, is when engineers come together to develop standard testing practices. These practices can then be used to negotiate contracts, determine performance, plan for operation and maintenance needs, and provide a foundation for consistent, repeatable, and reliable performance tests. Performance testing is built on three foundations : standards,measurements, and uncertainty. Each of these subjects will be discussed below.

Nomenclature

Abbreviations

ACC	Air Cooler Condenser
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
CSP	Concentrating Solar Power
CT	Current Transformer
CTI	Cooling Tower Institute
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
GSU	Generator Step-up transformer
HTF	Heat Transfer Fluid
NREL	National Renewable Energy Laboratory
POA	Plane of Array
PT	Potential Transformer
PTC	Performance Test Code
PV	Photovoltaic
PVUSA	Photovoltaics for Utility Scale Applications
RTD	Resistance Temperature Device
STC	Standard Testing Conditions
TBD	Test Boundary Diagram

Mathematical Variables

a_i	Linear coefficient for item i, where i = 1 to 4
E	Plane of Array Irradiance in W/m^2
T	Ambient Temperature in ºC
P	Power Output in kW
v	Velocity in m/s
X	Measurement value used to calculate corrected output
X_i	Measurement i
$X_{Ave,i}$	Average of measurement i
ΔX	Perturbation amount of measurement X

2. Testing standards

Many of the standards for testing solar energy generation are based on foundational work performed at the National Renewable Energy Laboratory (NREL). Much of the data that is used to locate solar fields has been gathered and organized into searchable database [2]. As solar energy, particularly PV, began to be used for utility scale energy production, the Photovoltaics for Utility Scale Applications (PVUSA) group was formed and wrote the foundational document for procurement, acceptance and rating practices for PV power plants [3]. The American Society for Testing and Materials (ASTM) codified the testing portion of this document in Standard Test Method E2848 [4]. ASTM is also currently working on a standard for determining reference conditions and expected capacity of non-concentrating PV systems [5], which will augment E2848. Since this standard will provide guidance on using historical data to determine reference conditions, it will also be useful for CSP technology to define the performance of the solar field.

Like PV based technologies, CSP technologies are also reaching the level of maturity where standard testing methods are being developed. Researchers at NREL have produced testing guides for parabolic trough CSP plants [6] as well as power tower CSP plants [7]. At the same time, ASME has formed a committee to produce a Performance Test Code for Concentrating Solar Power Plants (ASME PTC 52) [8]. The goal of ASME PTC 52 is to create an applicable testing standard that meets the needs of the solar industry. ASME PTC 52 will inevitably help with the inclusion of utility scale CSP in the current power market. Completion and acceptance of ASME PTC 52 will provide a contractual reference for new CSP plants that can be tested with repeatable results. ASME PTC 52 is intended to treat the solar field as a component in the overall facility, similar to the steam turbine generator which would be covered under other Performance Test Codes such as ASME PTC 6 [9] or ASME PTC 6.2 [10]. Testing the solar field as a component will help to provide acceptance in the traditional power generation industry.

CSP technologies have one major advantage over PV technologies in the traditional power industry in that power production is accomplished using traditional components. Ultimately, CSP technology transforms thermal energy into electrical energy through the generation and use of steam. Thus, other than the solar field, the technologies have an industrial familiarity. Figure 1 below shows a test boundary diagram (TBD) for a simplified CSP trough power plant, and Table 1 provides a listing of the relevant testing standards for component testing of CSP plants.

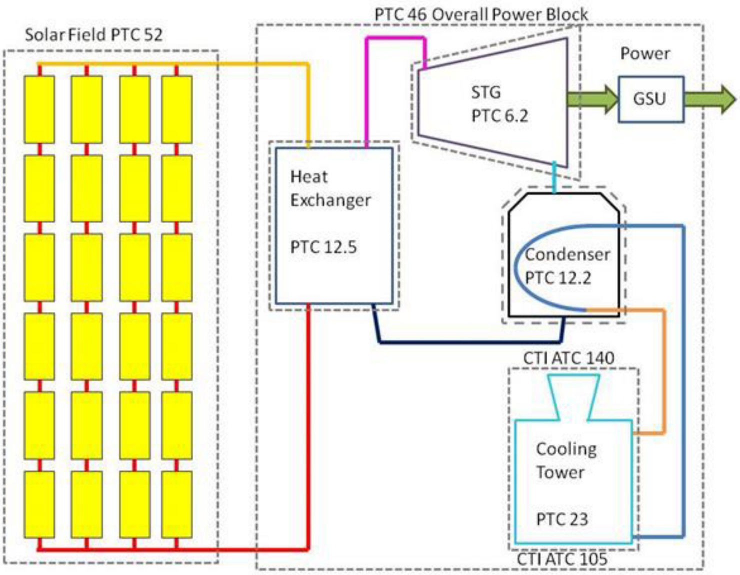

Fig 1. Simplified Test Boundary Diagram for a CSP Trough Plant.

Table 1. Performance Testing Standards for Component Testing in CSP Plants

Organization	Code Number	Revision Date	Title
ASME	PTC 6	2004	Steam Turbines
ASME	PTC 6.2	2011	Steam Turbines in Combined Cycles
ASME	PTC 12.2	2010	Steam Surface Condensers
ASME	PTC 12.5	2000	Single Phase Heat Exchangers
ASME	PTC 46	1996	Performance Test Code on Overall Plant Performance
ASME	PTC 52	TBD	Performance Test Code Performance Test Code for Concentrating Solar Power Plants
CTI	ATC 105	2000	Acceptance Test Code for Water Cooling Towers
CTI	ATC 107	2011	Test Code for Aircooled Condensers
CTI	ATC 140	2011	Isokinetic Drift Test Code

Performance testing for contractual acceptance or annual generation agreements is by definition the blending of a test standard and contractual obligations, boundaries, and limitations. Currently, no formal industrial standards have been accepted for use in evaluating the performance of the solar field portion of a CSP plant. In order to demonstrate the performance yesting process of the solar resource, testing of a PV plant using ASTM E2848 is used as an example. The performance test is configured by first defining the test boundary, which is often contractually specified, such as the one shown in Figure 2. The next step is to determine the input parameters that have the greatest effect on energy generation and to determine the reference values. In most cases, the reference conditions are defined by contract. Properly defined reference conditions depend on a high level of technical knowledge and effort by the contract author. In some cases, the values are stated directly; in others, standard testing conditions (STC) are referenced, or the contract could state that the reference conditions should be based on historical data. Careful evaluation and planning are required to determine the correct values that will be agreed to by all parties to the test. Table 2 below provides the Reference Conditions used in ASTM E2848 and the STC values for reference. For CSP, reference conditions may include parameters such as DNI, ambient temperature, turbidity, or mirror soiling. The selection of the reference conditions depends on the design configuration of the CSP plant.

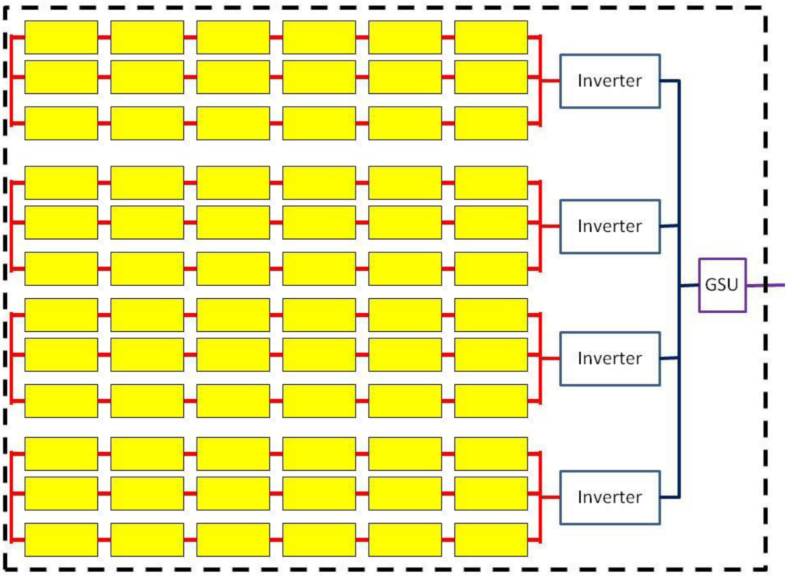

Fig 2. Test boundary diagram for PV solar energy generation system

Table 2. Reference Conditions for ASTM E2848

Test Condition	Symbol	STC Value
Plane of Array (POA) Irradiance	E	1000 W/m^2
Ambient Temperature	T	25 ºC
Wind Velocity	v	1 m/s

Another major contribution of ASTM E2848 is providing a method to filter and eliminate data from the analysis. There are ten criteria listed in Section 9.0 of the test method that are used as a starting point. Contractual limitations can modify these conditions or add additional criteria. In order to limit the effect of solar variability, the overall test is broken into a series of fifteen-minute Test Periods. Typically, a successful test will have at least fifty test periods that meet the selection criteria. The configuration of the data selection criteria requires that data be collected for a minimum of three days and at most four weeks. This is much longer than is typically allotted for a performance test of a traditional energy production facility, and must be understood and accounted for properly in the schedule and planning of the project.

With the test boundary, measurements, data selection criteria and reference conditions determined, the correction methodology can be defined. In the case of ASTM E2848, the correction is based on a multiple parameter linear regression of the measurements as defined in equation 1. Example testing data is shown in Figure 3. Once the regression analysis is complete, the reference conditions are substituted back into equation 1 to calculate the corrected output which is compared to the contractual guarantees. While ASTM E2848 provides a good approach that is generally accepted, it is not the only approach used. Since the technical community has not come together behind a single standard testing method, there is still a great deal of ambiguity that has to be worked through and negotiated as part of the test preparations.

$$P = E(a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v) \quad (1)$$

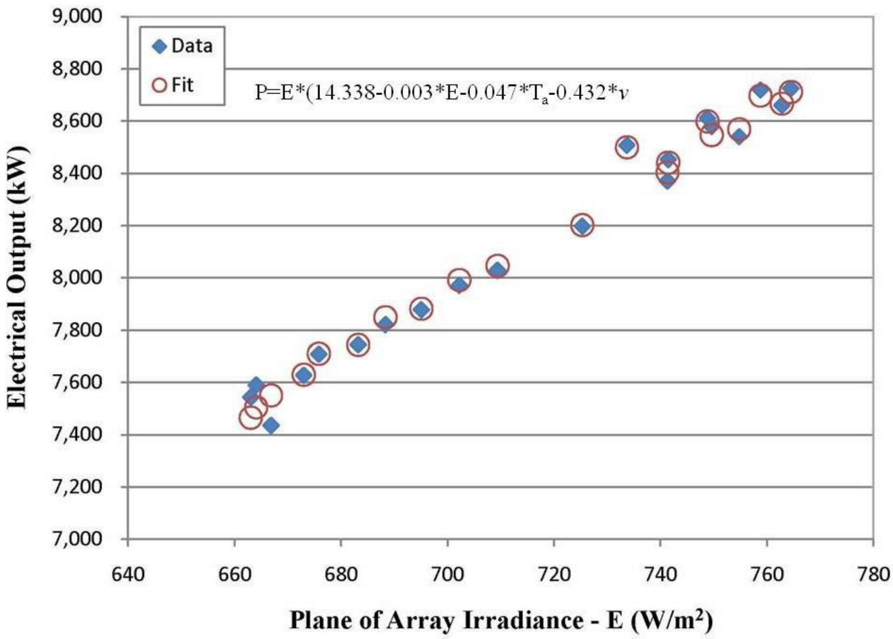

Fig 3. Example of filtered data and fit data based on multiple parameter linear regression.

3. Measurements

One of the most important goals of a standard test practice is to provide guidance on the critical measurements. Many times this is based on experience in the development committee, and other times it requires good engineering judgment and a simple TBD. Figure 1 shows a simplified TBD for a CSP plant. With the TBD established, it becomes straightforward to determine what energy streams enter and exit the system. For this simplified case, there are environmental effects, solar irradiance, ambient temperature, wind speed, and soiling. If only the solar field is considered, as indicated by the ASME PTC 52 test boundary, the inlet and exit conditions of the heat transfer fluid (HTF) are primary measurements. In order to define inlet and exit conditions, measurements of the temperature, pressure, and flow rate of the HTF must be made. Ultimately, the output of the plant is electrical power which must be corrected to the contractual reference conditions, which is done using ASME PTC 46. At this point, contractual guidance is required to best determine the measurement requirements. If the power output is referenced to the energy input provided by the HTF, then environmental measurements may not be required. However, if the contractual reference conditions include ambient conditions, then the energy provided by the HTF must be corrected to those conditions prior to being applied in the ASME PTC 46 analysis. Herein lies the difficulty for CSP plant performance testing: all ASME PTC 46 tests have some form of ambient temperature correction that is typically applied through the heat rejection system (typically a cooling tower or air-cooled condenser). If the procurement contract for the overall plant does not explicitly exclude these ambient temperature effects on the solar field, corrections for the energy provided by the HTF as a function of the ambient temperature must be provided by the solar field manufacturer. The other option would be to use an ASME PTC 52 performance test of the solar field to correct the HTF energy output of the system, which would require corrections for all of the ambient conditions. This case assumes that the auxiliary loads to operate the plant are internal to the boundary and not externally supplied. Discussions of these primary measurements are provided below.

3.1 Ambient measurements

Ambient measurements can be relatively straightforward. Most power plants have a weather station to monitor the typical ambient conditions of temperature, barometric pressure, relative humidity, wind speed and wind direction, such as the one in Figure 4a. In the case of solar generating plants, there is additional instrumentation for solar irradiance. In general, weather stations are configured to measure the global horizontal irradiance (GHI) with some form of pyranometer. In special cases, there may be a second measurement for diffuse horizontal irradiance (DHI). In the case of CSP plants, at least one pyrheliometer or rotating shadow band pyranometer is provided to measure the direct normal irradiance (DNI). NREL provided an excellent reference document with recommendations for instrument selection [2]. ASTM E2848 testing requires that the irradiance measurement be plane-of-array (POA). This is another special case where the sensor is either mounted on the plane of the solar module, or POA irradiance is calculated from the GHI and the angle of the array. Performance engineers must be careful to specify the correct measurement based on the agreed-upon test method.

One of the more complicated measurements in the environment is soiling. Soiling is the accumulation of dirt and grime on the surface of the PV modules, which blocks the solar irradiance and reduces the power output [11]. A similar effect may be seen for dirt accumulation on the reflector elements in a CSP plant. For short duration tests, this may not be as critical of a measurement. However, if data is to be collected over a longer duration such as a year this can become a critical factor. The measurement of this parameter requires that enough sensors be distributed though the field to match the expected panel cleaning routine, and attempt to capture the spatial distribution. The determination of soiling percentage is derived from the measurement of a dual reference cell such as an Atersa MET MODULE shown in Figure 5. In order to determine the soiling, one cell is periodically cleaned while the second is allowed to soil naturally. Both sensors are cleaned during the module/reflector cleaning in the region near the sensor, thus resetting the soiling measurement. Additionally, for CSP reflectors, reflectometers are available to measure soiling effects.

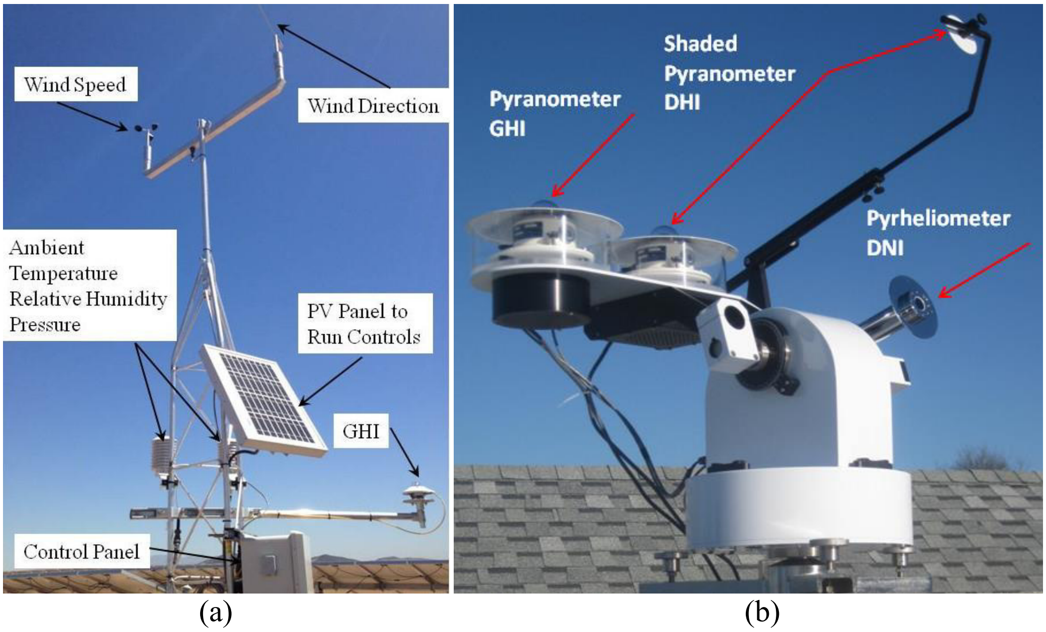

Fig 4. Example of ambient weather station for a solar generation facility (a) and solar irradiance measurement devices (b)

Fig 5. Example of dual reference cell soiling sensor, from Atersa brochure.

The final ambient measurement that is required for PTC 46 testing is the temperature at the inlet to the heat rejection unit. The measurement type depends on the type of heat rejection unit in operation. If the heat rejection unit is a water based cooling tower, then the ambient wet bulb temperature must be measured at the inlet. This measurement is typically not included in station instrumentation and requires temporary instrumentation be installed. This measurement is made using a mechanically ventilated psychrometer with a measurement device such as a resistance temperature device (RTD) inserted into a cotton wick. The wick is continuously wetted by a reservoir of distilled water. Similarly, if the heat rejection unit is an air-cooled condenser (ACC), then temperature sensors are positioned at the inlet of the mechanically aspirated psychrometer, but a wetted wick is not used.A dry bulb temperature measurement, with radiation shielding, is thus made. The number of these instruments is not clearly defined in ASME PTC 46 but is based on size and configuration of the heat rejection unit.

3.2 HTF measurements

HTF measurements should be similar to those for any other thermodynamic working fluid. The three primary measurements are temperature, pressure, and flow. In many cases, the HTF is a liquid such as water, glycol or mineral oils. These measurements typically only require that provisions have been made in the piping for the measurement such as the installation of test thermowells for temporary temperature measurements. Pressure measurements are similar. They can either be made using provided measurement taps, or by installing temporary instruments on the vents of the station instruments. In either case, the distance from the pressure tap to the measurement device must be measured to correct forelevation head in the sensing lines. This also requires that the physical properties of the HTF be known so these calculations are appropriate to the material. Flow measurement is typically made in parallel with a station provided flow element. For this reason, it is essential that calibration information for all primary flow elements be provided to the performance test engineer as soon as possible in the preparation and development stage. Advances in CSP technology have led to the use of molten salts as HTFs. The determination of operating parameters of these materials will require input from either the HTF manufacturer or the instrument specialist at the CSP facility.

3.3 Power output measurement

The final primary measurement is the facility power output. Typically, this measurement is made on the high side of the generator step-up transformer (GSU) and is based on the planned power purchase agreement measurement location. The measurement should be made with a revenue quality power meter using calibrated potential transformers (PT) and current transformers (CT). In many cases, a calibrated temporary power meter can also be installed for short duration testing. The selection of the measurement options improves the quality of the measurement and therefore reduces the uncertainty.

Depending on the desired limits on test uncertainty, station instruments may be used for many of the ambient and HTF measurements. If strict test uncertainty limits are required, the use of recently calibrated temporary instruments can often reduce the overall plant test uncertainty. Additionally, the use of temporary instrumentation can increase the number of measurement locations thus better defining the spatial variation of the measurements and thus reducing the uncertainty. A basic overview of uncertainty is provided in section 4.

4. Uncertainty analysis

Uncertainty analysis, based on the instrument error as well as the random measurement error, establishes the quality of the test.. Uncertainty analysis for power plant testing is generally based on the guidance and structure provided in ASME PTC 19.1 [12]. Based on this structure, uncertainty is broken into two major categories: systematic and random uncertainty. Measurement sensitivity is used to combine individual measurement uncertainties into a combined calculated result to determine the effect of systematic and random uncertainties of a particular measurement on the overall result. The systematic and random components of measurement uncertainty are then combined with a root sum square technique. Then, individual measurement uncertainties are combined using a root sum square technique to determine the test uncertainty.

Systematic uncertainty is comprised of instrument accuracy and spatial uncertainty. While instrument accuracy is straightforward and provided by the manufacturer in many cases, calculating spatial uncertainty requires judgement and experience. Spatial aspects of soiling have already been discussed; another big unknown with spatial variation in solar energy generation performance testing is measurement of the incoming energy. For solar energy performance testing, determination of the irradiance is a key factor in determining the uncertainty. Unlike traditional power plants, the energy source is unstable and can vary on a minute by minute basis as well as from point to point, or spatially. The standard approach to this is to use only one instrument, restricting the testing to clear solar days and assuming the spatial variation is equal to zero [6,7]. Unfortunately, this approach does not work well with the fluid schedules associated with commissioning, and may not provide the best reference value for financial planning. An approach has been suggested to use aerial observation to increase the resolution of the irradiance measurements and thus reduce the uncertainty [13,14]. Figure 6 provides a suggested instrument configuration which includes pyranometers with two different levels of accuracy and a distant observer platform. While these papers and the measurement technique were initially conceived to measure DNI the same technique could be easily used for GHI as well.

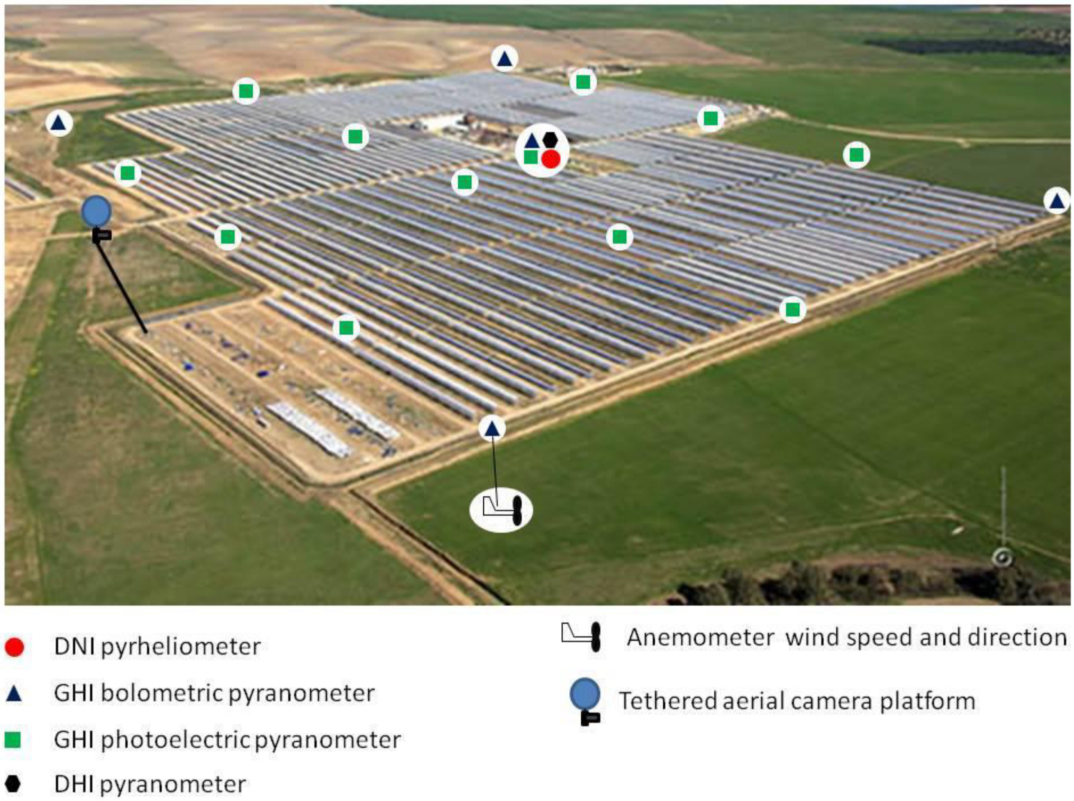

Fig 6. Potential instrument distribution on a trough style CSP plant to reduce spatial uncertainty on an other-than-clear solar day.

Random uncertainty consists of two parts: standard deviation of the mean and Student's *t* value. The standard deviation of the mean defines the random temporal variation in the data while the Student's *t* value is used to apportion the random error based on a set confidence level. For performance testing, a 95% confidence level is used, thus encompassing nearly all of the random variations in the measurements.

The final key to evaluation of test uncertainty is the evaluation of the sensitivity of the final corrected result to a given input parameter. Sensitivity is the instantaneous rate of change in a result to the variation in a test parameter. To calculate the sensitivities using a correction model, the variations in correction results are first evaluated for each input parameter at the measured value during the test. The user then recalculates the result when the input measurement deviates by a small amount, or $X_i = X_{Ave,i} + \Delta X$. Because the order of the error in the calculated sensitivity depends on the size of ΔX, a small value should be chosen. For increased accuracy, a central differencing method can be used, where the absolute sensitivity is calculated at $X+\Delta X$ and $X-\Delta X$.

With the main categories of uncertainty defined, the sensitivity is used to apportion the effect of each measurement on the final corrected result. The sensitivity of each measurement is multiplied by the systematic and random uncertainty for each measurement. A root sum square of the component uncertainties then provides the overall uncertainty of the measurement. By taking the root sum square of the overall uncertainty for each measurement, the overall uncertainty of the test can be determined.

5. Conclusions

Performance testing provides a pathway for solar energy generation to gain acceptance as part of the overall power generation community. Through performance testing, owners gain a better understanding of the operational status of the facility; grid operators have a concept of the available energy generation potential; manufacturers have consistent approaches for contractual negotiation, and all parties have a way to compare results between different plants. This approach absolutely dictates that common standard practices be developed and accepted by the power generation community. These standards have to address measurement points, correction methods, and ultimately test uncertainty. Once this is achieved, solar energy generation will have officially transitioned from large scale laboratory experiment into the industrial norm. Then and only then will solar energy generation be able to stand amongst the traditional energy generation technologies.

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